A Bright Lunar Impact Flash Linked to the Virginid Meteor Complex

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Stanford Meteor Environment and Effects Workshop
Stanford University, California, 14-16 July 2015

Overview

On 17 March 2013 at 03:50:54 UTC, NASA detected a bright impact flash on the Moon caused by a meteoroid impacting the lunar surface.

There was meteor activity in Earth's atmosphere the same night from the Virginid Meteor Complex.

The impact crater associated with the impact flash was found and imaged by Lunar Reconnaissance Orbiter (LRO).

9-year observing program

Goal: Monitor the Moon for impact flashes produced by meteoroids striking the lunar surface. Determine meteoroid flux in 10's g – kg size range.

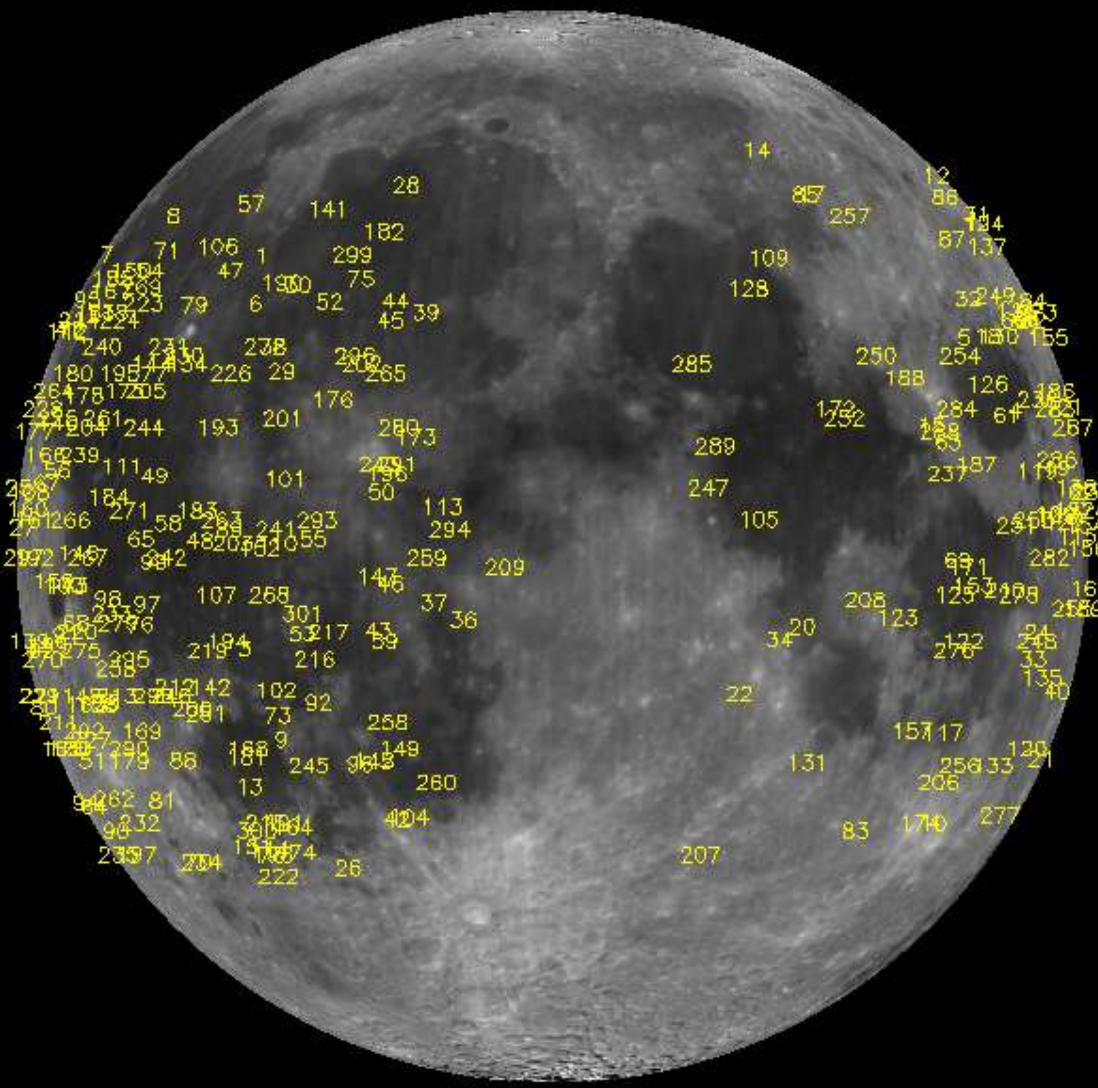
Observation from MSFC

- Two 0.35m telescopes simultaneously
- Black & white CCD video cameras
- Interleaved 30fps video digitized, recorded
- Video analyzed with custom software

Field of View

- FOV covers approx. 20 arcmin
- $4{\times}10^6$ km^2 on the leading or trailing edge
- Observing when illumination 10-50%
- Maximum 10 observing nights/month

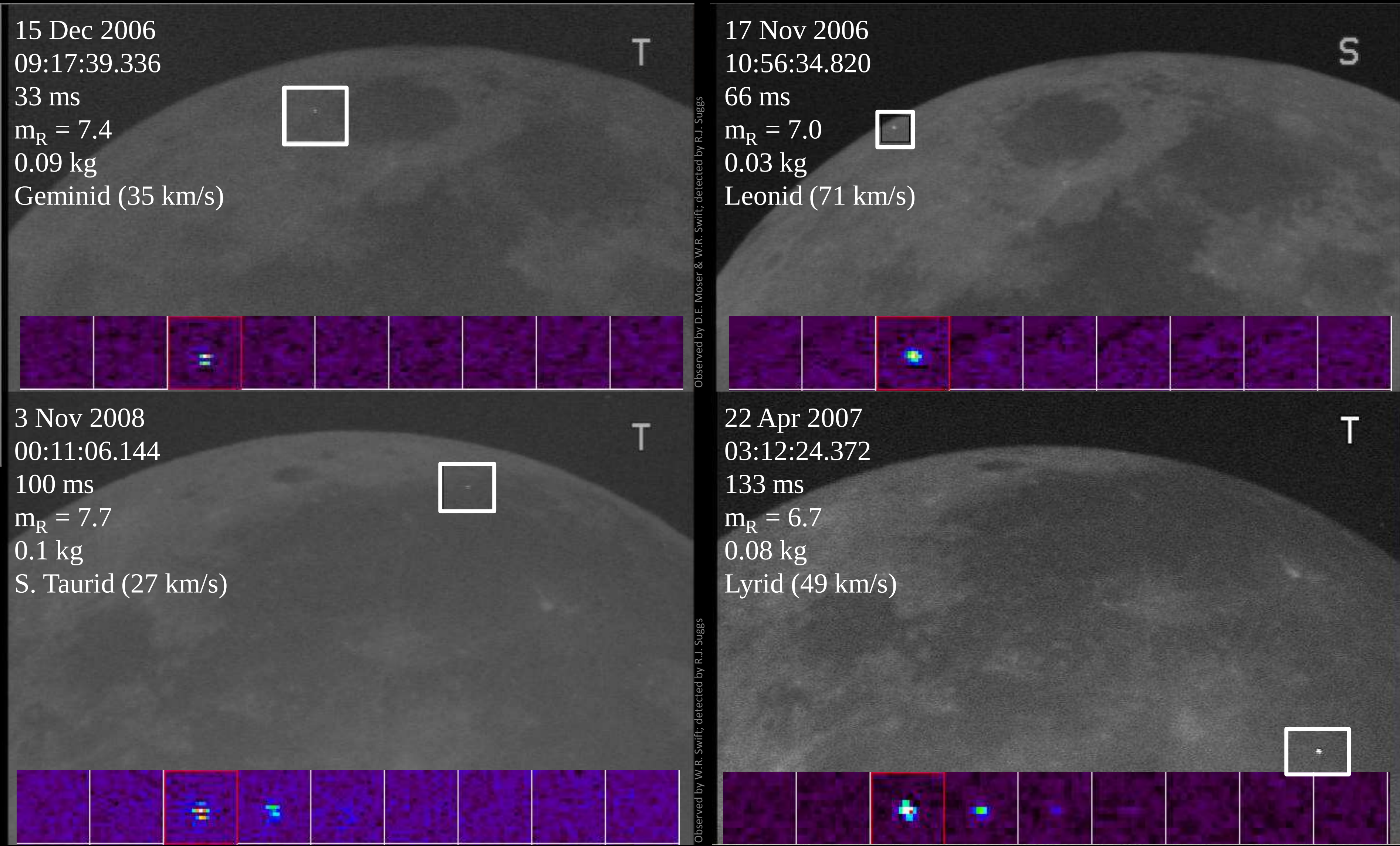
330+ Lunar impacts observed



For more info:

Suggs et al. (2014)
Suggs et al. (2011)
Suggs et al. (2007)

Typical impact flashes



Atypical flash on 17 March 2013

Observed by A. Kingery & R.M. Suggs; detected by R.J. Suggs

Flash info

Detected with two 0.35 m telescopes

Watec 902H2 Ultimate monochrome CCD cameras

- Manual gain control
- gamma = 0.45

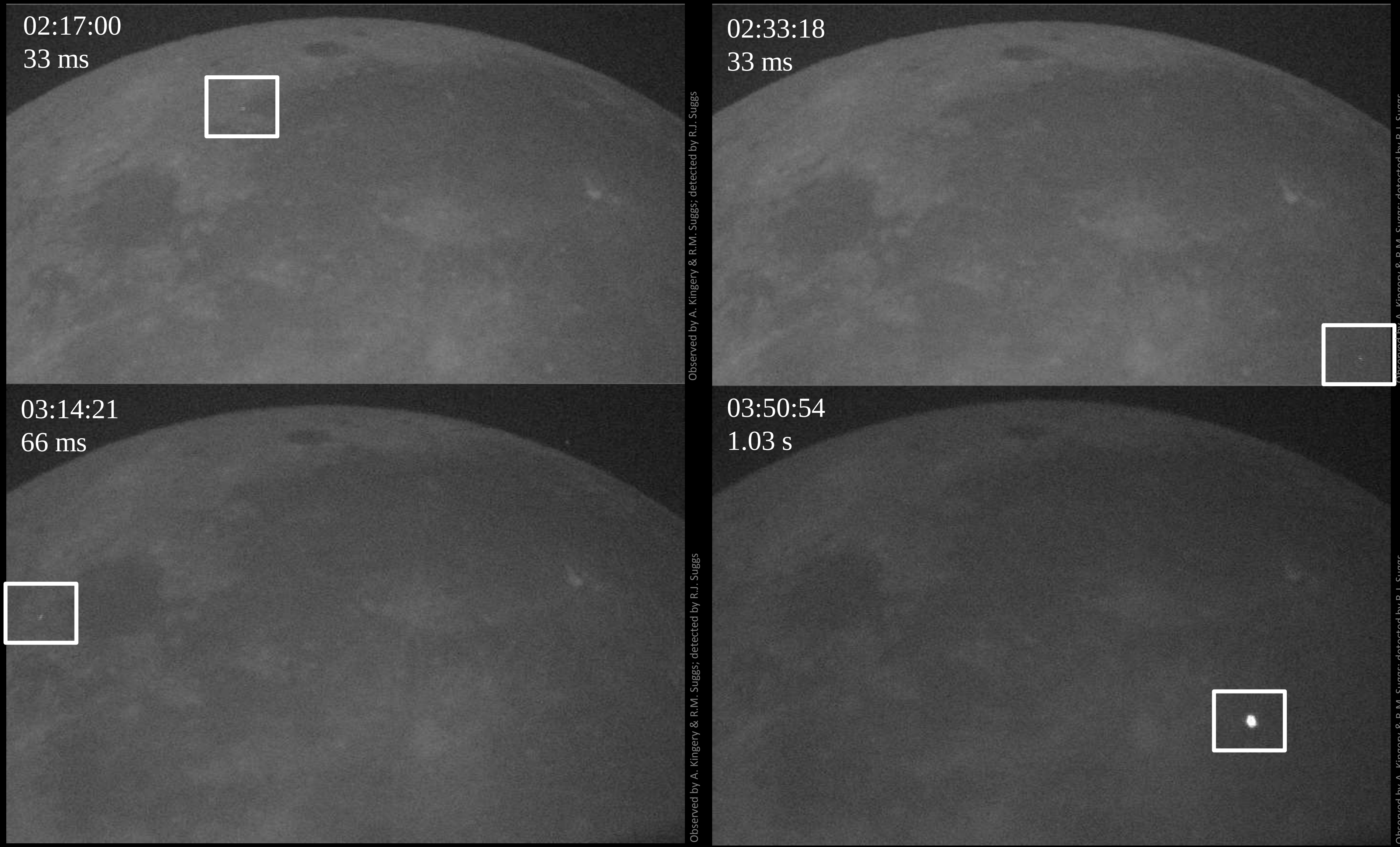
Saturated → needed saturation correction!

- Photometry performed using comparison stars (Suggs et al. 2014)
- 2D elliptical Gaussian fit to unsaturated wings of PSF

Peak $m_R = 3.0 \pm 0.4$

Lum energy = $7.1^{+3.9}_{-2.4} \times 10^{6}$ J

Increased lunar activity on 17 Mar 2013



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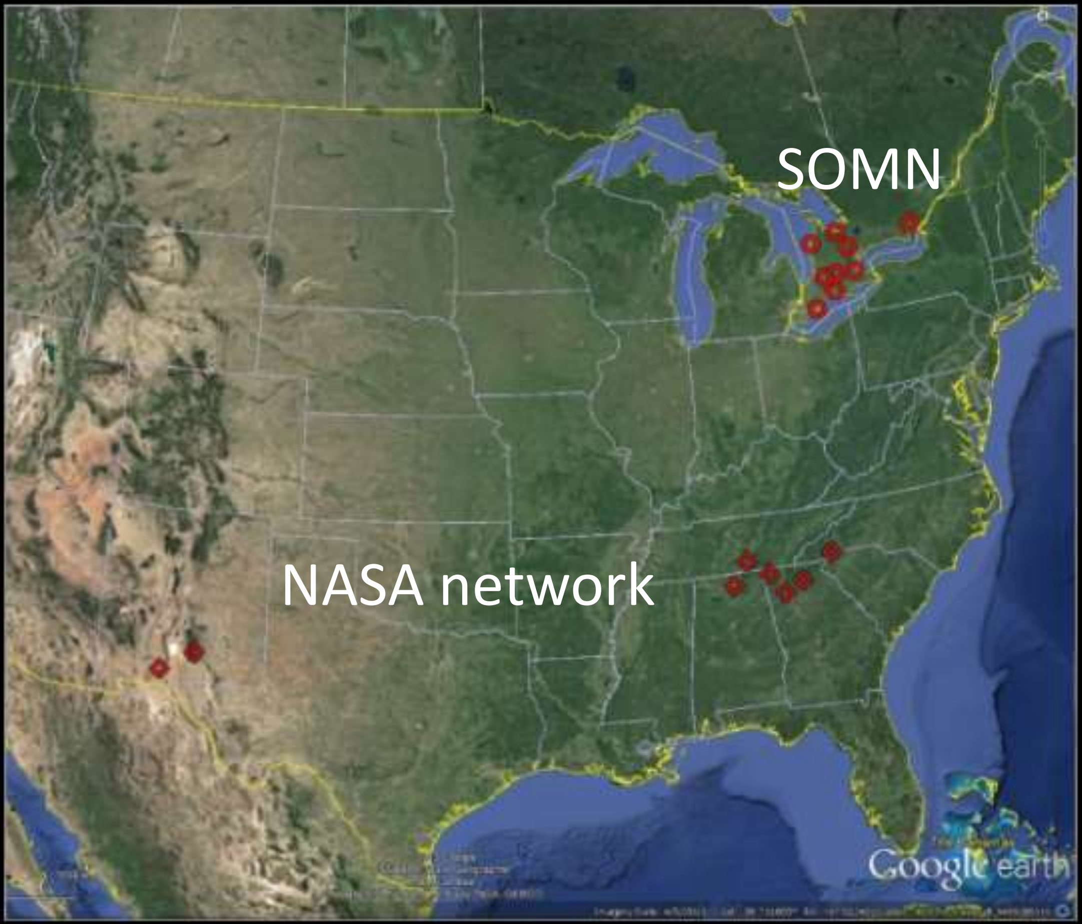
Meteor activity on 17 Mar 2013



19 meteors were observed by NASA & SOMN all-sky meteor cameras on 17 Mar 2013

Meteor shower activity on 17 Mar 2013 (SOMN & NASA)

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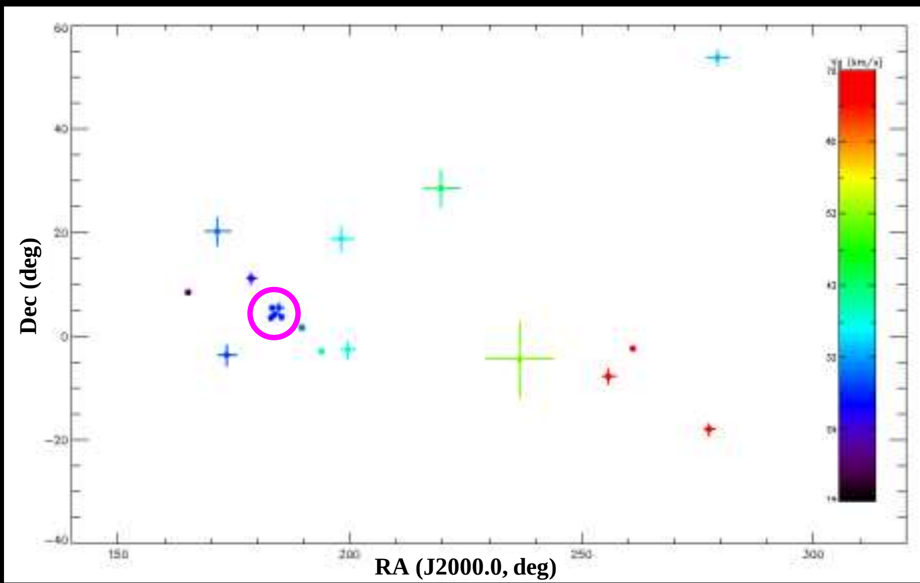
NASA

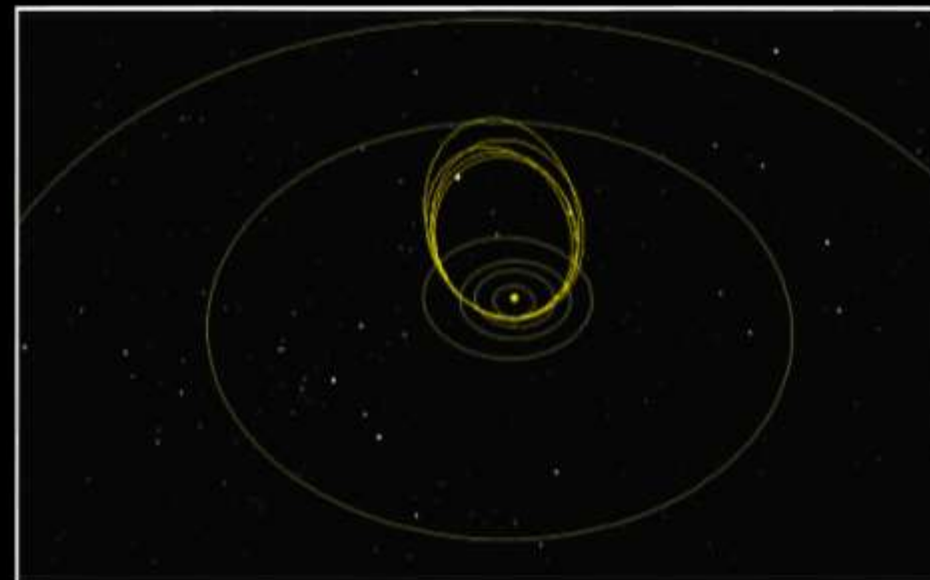
19 meteors seen on 17 Mar 2013



Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with:

	meteors
α_g (°)	184.1 ± 1.0
δ_g (°)	4.4 ± 0.9
v_g (km/s)	25.6 ± 0.8
λ_{sun} (°)	356.6

Cluster of 5 seen on 17 Mar 2013



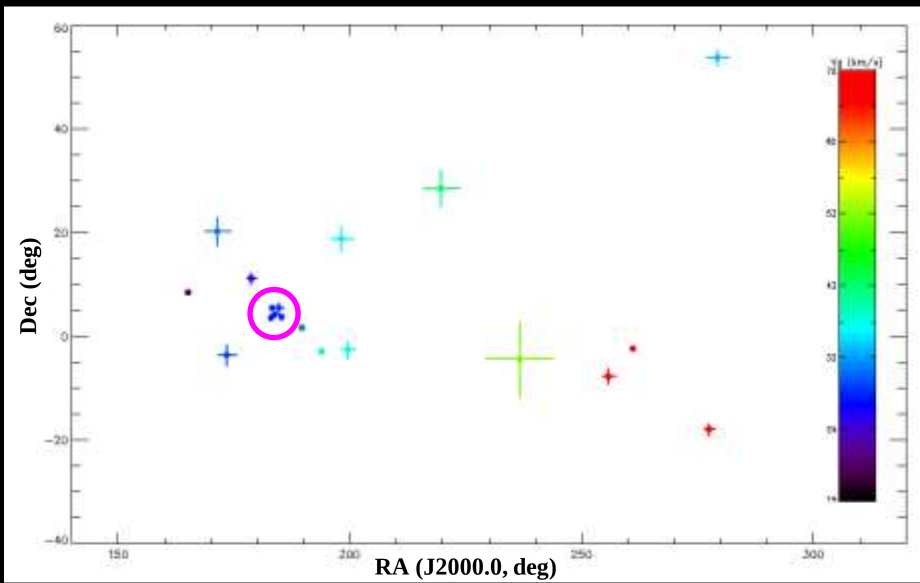
Orbits of the cluster of 5 were very similar with the following average orbital elements:

	meteoroids
a (AU)	2.25 ± 0.17
e	0.79 ± 0.02
i (°)	5.26 ± 1.02
ω (°)	280.32 ± 2.11
Ω (°)	356.65 ± 0.07
q (AU)	0.48 ± 0.02
Q (AU)	4.0 ± 0.3
Tj	3.1 ± 0.2 ⟶ Indicates ~asteroidal body

Meteor shower activity on 17 Mar 2013 (SOMN & NASA)

JACOBS ESSSA Group

19 meteors seen on 17 Mar 2013

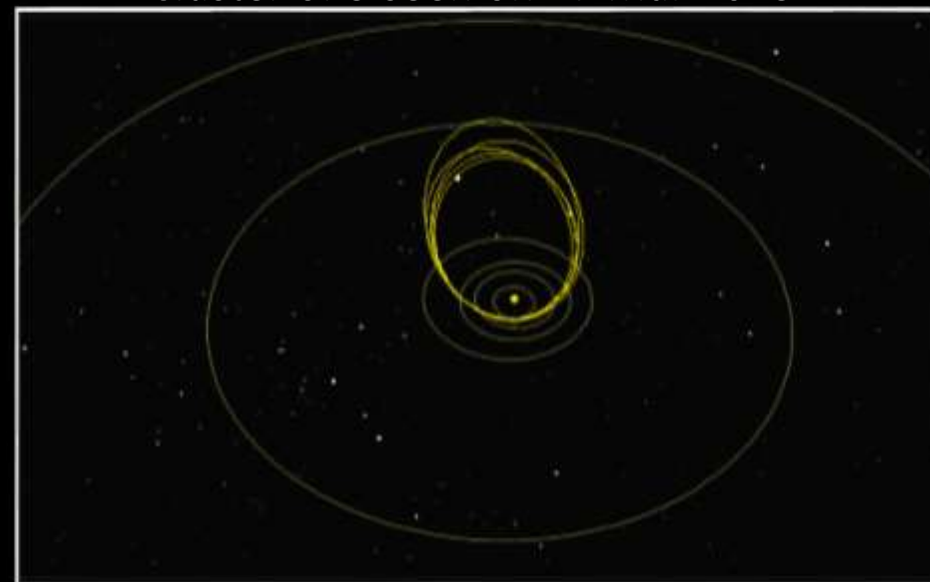


Geocentric meteor radiants color-coded by speed with a tight cluster of 5 with:

	meteors	NVI[1]	EVI[2]
		Virginid Complex (rad at λ=356.6)	
α_g (°)	184.1 ± 1.0	183.1	181.0
δ_g (°)	4.4 ± 0.9	2.3	4.7
v_g (km/s)	25.6 ± 0.8	23.0	28.9
λ_{sun} (°)	356.6	354	354

[1]Sekanina (1973), [2]Whipple (1957)

Cluster of 5 seen on 17 Mar 2013



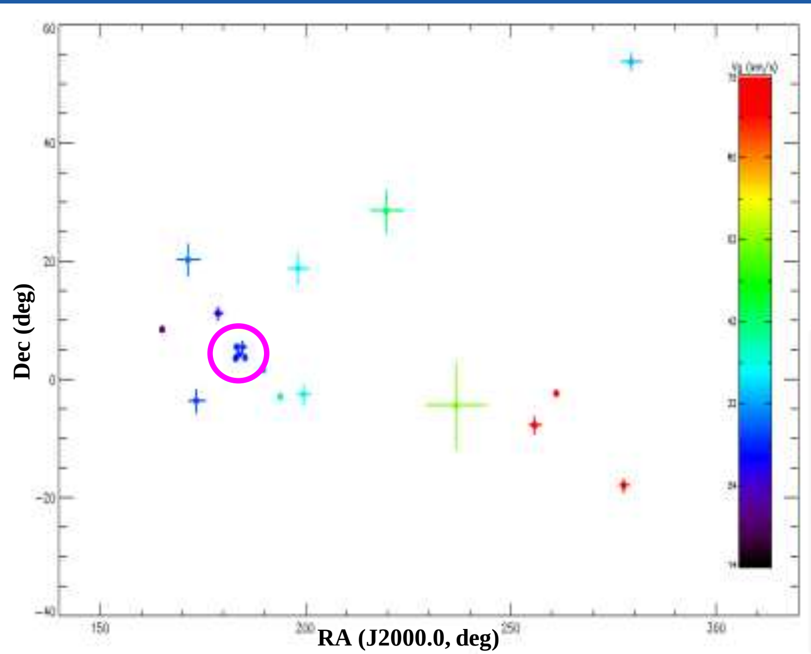
Orbits of the cluster of 5 were very similar with the following average orbital elements:

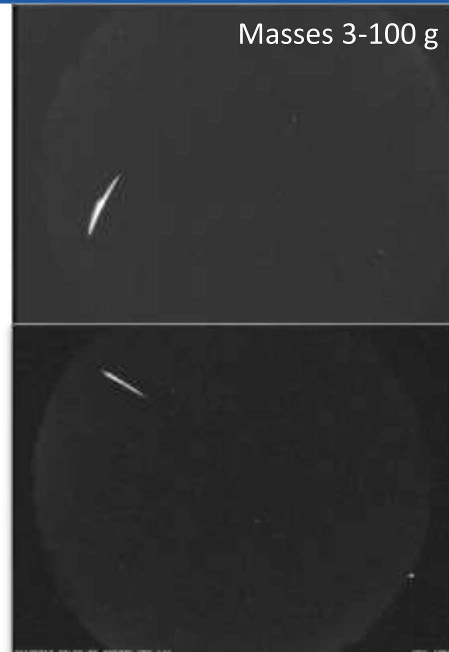
	meteoroids	NVI	EVI
a (AU)	2.25 ± 0.17	1.69	2.82
e	0.79 ± 0.02	0.71	0.86
i (°)	5.26 ± 1.02	3.7	5.2
ω (°)	280.32 ± 2.11	282.4	285.8
Ω (°)	356.65 ± 0.07	358.0	355.1
q (AU)	0.48 ± 0.02	0.496	0.40
Q (AU)	4.0 ± 0.3	2.89	5.25
Tj	3.1 ± 0.2 →	Indicates ~asteroidal body	

Favorable Virginid radiant geometry

Pink indicates the portion of the moon visible to the radiant.
Impact angle ~56° from horizontal.

Putting it all together





All-sky meteor cameras detected a deeply penetrating cluster of 5 meteors on 17 March.

Radiant and orbital elements consistent with the Virginid Meteor Complex (EVI/NVI).

Impact flash rate increased to 1 every 0.87 hours on 17 March. (4 impacts in 3.5 hours)

Impact Constraints

Assume impact flash was part of Virginid Meteor Complex

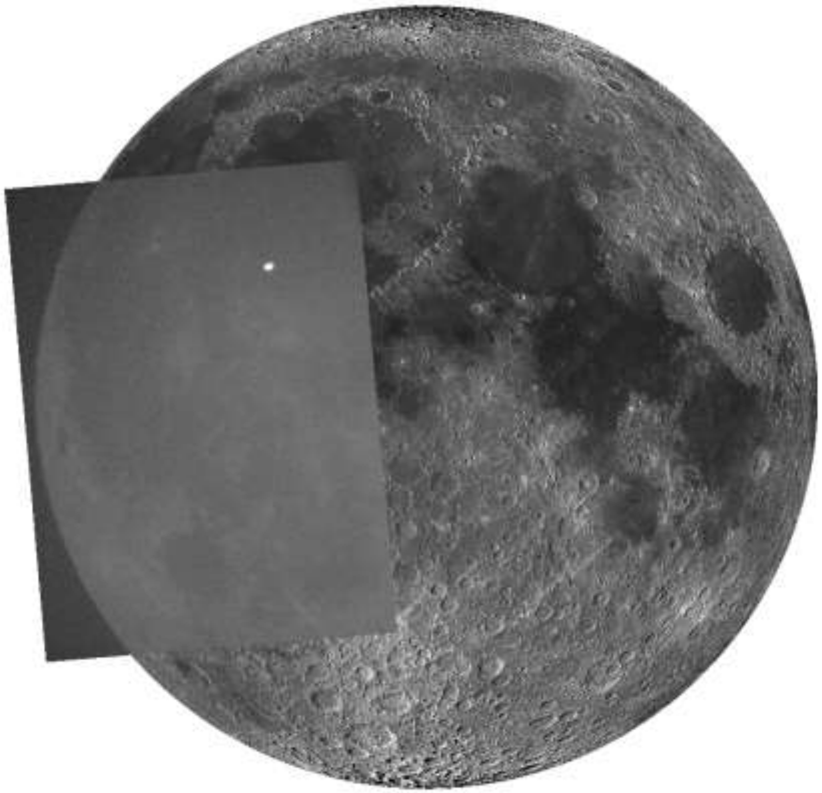
➡ $v_g = 25.6$ km/s

➡ $\theta_h = 56°$

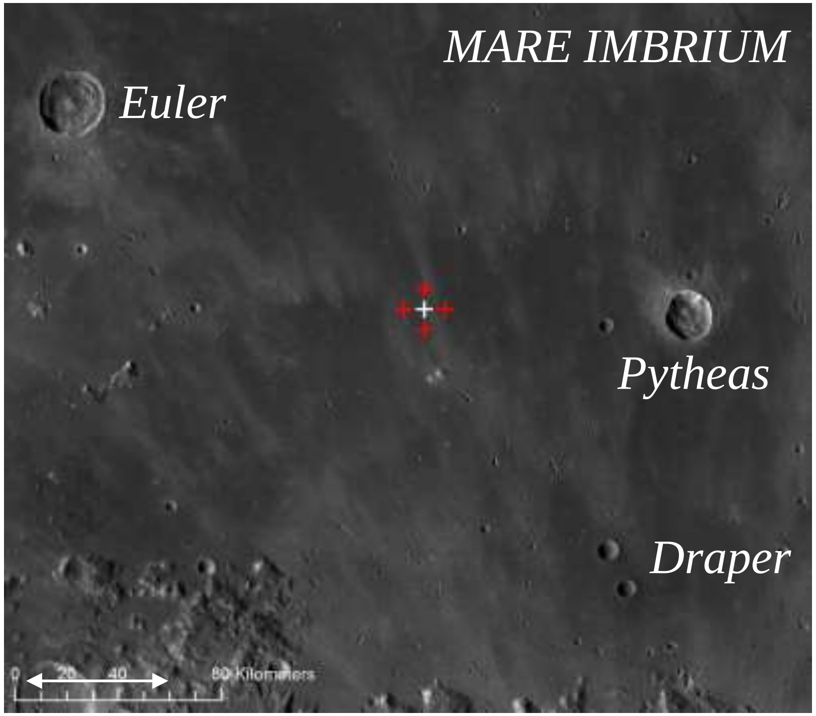
➡ Asteroidal? ($T_j = 3.1 \pm 0.2$)

Mapping the impact location

LRO basemap



Using the intensity-weighted center of the flash



ArcMap was used to selenoreference the lunar impact following a newly developed selenolocation workflow.

Final predicted crater position

$20°.684 \pm 0.258$ N, $24°.228 \pm 0.288$ W

Impact crater found by LRO!

Robinson et al. (2014)

Image from Robinson (2013)

NASA/GSFC/Arizona State University

Features
- Fresh, bright ejecta
- Circular crater
- Asymmetrical ray pattern

Crater info
- Rim-to-rim diameter = 18 m
- Inner diameter = 15 m
- Depth ≈ 5 m

Actual crater location
- 20.7135° N, 24.3302° W

Impact Constraints

➡ Circular crater, impact angle constrained $\theta_h > 15°$

➡ Ejecta gives no azimuth constraint (Robinson, personal comm. 2014a)

Comparison of geolocation results to obs crater location

Method	Longitude (° W)	Latitude (° N)	Angular distance from observed (°)	Surface distance from observed (km)
Workflow	24.228±0.288	20.684±0.258	0.10026	3.041
LRO observed	24.3302	20.7135	-	-

Transient crater diameter estimates

Assumptions: Virginid v_{gfoc}=25.7 km/s, θ_h = 56°; ρ_t = 1500 kg/m^3 (regolith)

Model	Lum eff. η	KE $\times 10^9$ (J)	Mass (kg)	ρ_p (kg/m^3)	D_{calc} (m)	D_{obs} (m)	% Err
Gault's crater scaling law (Gault 1974)	5×10^{-4} (Bouley et al. 2012)	14 [9.4,22]	42 [28,66]	1800	18.5 [16.5,21.1]	15	23%
				3000	20.2 [18.0,23.0]	15	35%
	1.3×10^{-3} (Moser et al. 2011)	5.4 [3.6,8.4]	16 [11,26]	1800	14.1 [12.5,16.0]	15	6%
				3000	15.3 [13.6,17.4]	15	2%
Holsapple's online calculator (Holsapple 1993)	5×10^{-4} (Bouley et al. 2012)	14 [9.4,22]	42 [28,66]	1800	12.2 [10.9,13.8]	15	19%
				3000	12.5 [11.1,14.2]	15	17%
	1.3×10^{-3} (Moser et al. 2011)	5.4 [3.6,8.4]	16 [11,26]	1800	9.3 [8.3,10.5]	15	38%
				3000	9.5 [8.5,10.8]	15	37%

Two example values of η from the literature yield large ranges for KE and mass. Consequently, model results are highly dependent on luminous efficiency η.

Assuming a velocity dependent $\eta = 1.3\times10^{-3}$, these model results are consistent with the observed crater diameters.

D_{calc} = 8-18 m transient crater

D_{calc} = 10-23 m rim-to-rim

D_{obs} = 15 m inner ('transient')

D_{obs} = 18 m rim-to-rim

Impact summary

Date of impact:	17 March 2013 3:50:54 UTC
Duration of impact:	1.03 s
Corrected flash peak R magnitude:	3.0 ± 0.4
Luminous energy generated by impact:	$7.1^{+3.9}_{-2.4} \times 10^6$ J
Estimated kinetic energy of impactor:	$5.4^{+3.0}_{-1.8} \times 10^9$ J = 1.3 tons of TNT (assuming $\eta = 1.3 \times 10^{-3}$)
Estimated mass of impactor:	16^{+10}_{-5} kg (assuming v = 25.7 km/s)
Estimated diameter of impactor:	22 ± 3 cm (assuming ρ_p = 3000 kg/m^3)
Crater diameter:	18 m rim-to-rim, 15 m inner ('transient')
Crater location:	20.7135° N, 24.3302° W
Possible meteor shower association:	Virginid Meteor Complex

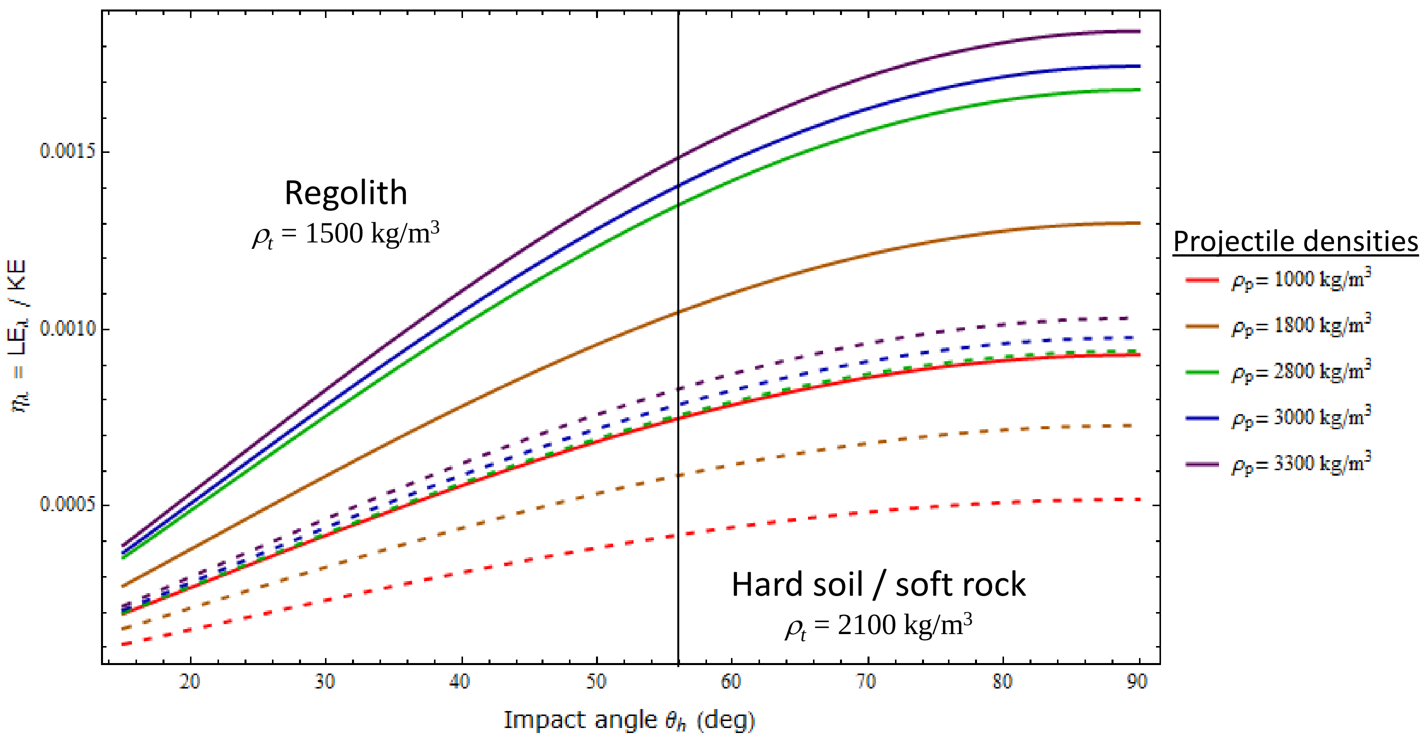
Backup Slides

Luminous efficiency: $LE_\lambda = \eta_\lambda KE$

D_t = 15 m from crater measurements
$LE_\lambda = 7.1 \times 10^6$ J from flash measurements

Gault's crater scaling law (Gault 1974) rearranges to give η_λ vs θ_h without assuming impact speed.

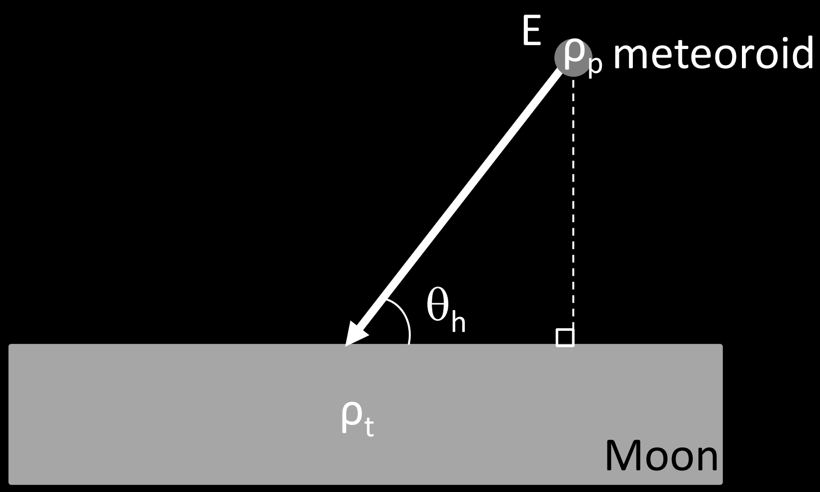
$$\eta_\lambda = LE_\lambda / KE = LE_\lambda / (4.0\, D_t\, \rho_p^{-0.167}\, \rho_t^{0.5} \sin^{-1/3}\theta_h)^{1/0.29}$$



Typical values of η_λ derived from lunar regolith range from $2 \pm 1 \times 10^{-4}$ to $2 \pm 1 \times 10^{-3}$.

Assuming association with the Virginids, $\theta_h = 56°$ and $7.5^{+4.5}_{-2.5} \times 10^{-4} < \eta_\lambda < 1.5^{+0.8}_{-0.5} \times 10^{-3}$.

Crater scaling laws



Gault's scaling law (Gault 1974) for D < 100 m

$$D = 0.25\rho_p{}^{0.167}\rho_t{}^{-0.5}E^{0.29}(\sin\theta_h)^{1/3}$$

D = transient crater diameter

ρ_p = projectile density

ρ_t = target density

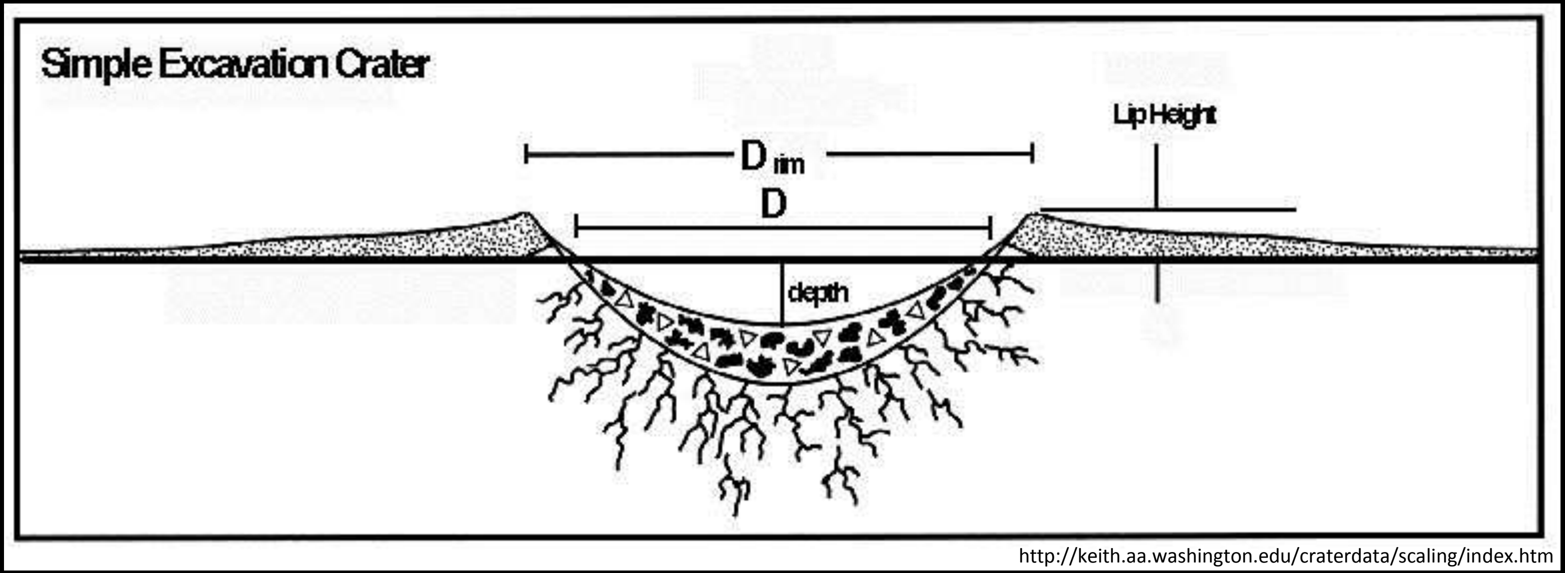
E = kinetic energy of projectile

θ_h = impact angle measured wrt horizontal

Holsapple crater calculator

(http://keith.aa.washington.edu/craterdata/scaling/index.htm)

Crater scaling laws



D

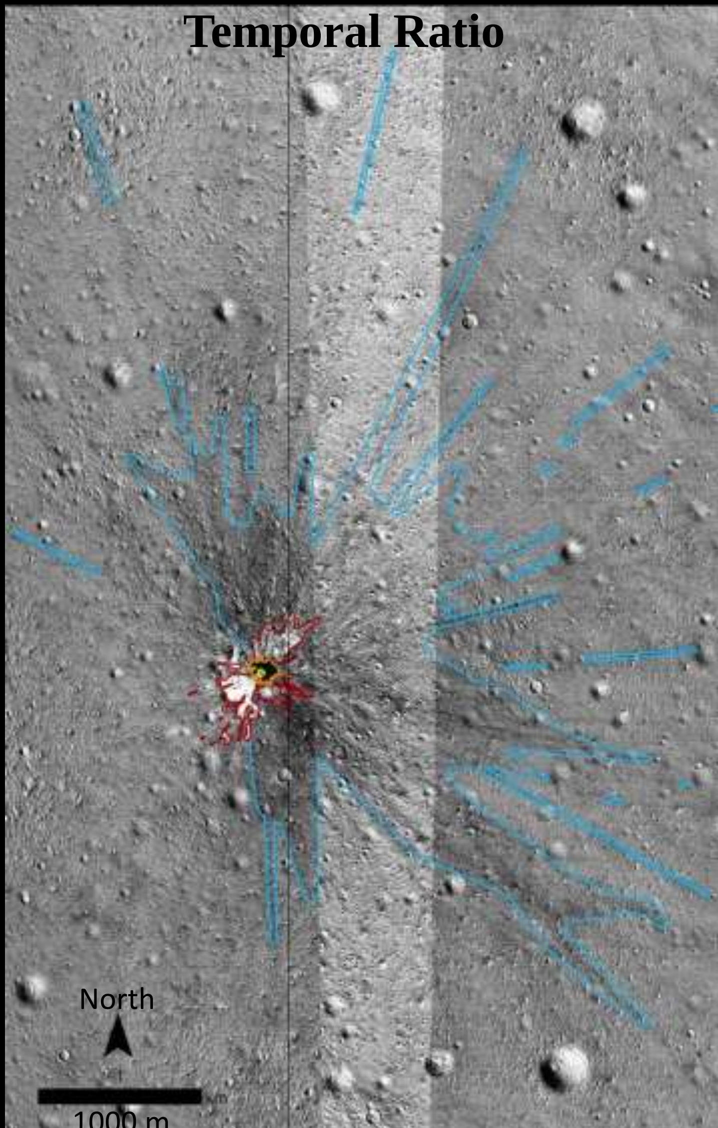
- Transient crater diameter
- Measured at the height of the pre-existing surface
- Aka inner diameter, apparent diameter

D_{rim}

- Crater rim diameter
- Measured from rim to rim
- Aka outer diameter

Holsapple assumes $D_{rim} = 1.3D$ similar to Melosh (1989)

Ejecta distribution
after Robinson et al. (2014)



Robinson et al. (2014)

Ejecta in multiple reflectance "zones"

High reflectance zone 10-20 m SW, <10 m NE
Low reflectance zone 50 m WSW, 80 m ENE
High reflectance zone ~300 m rough semicircle
Low reflectance zone ~1 km centered in NE
248 circ/irreg splotches within 30 km

See Robinson et al. (2014) for more details

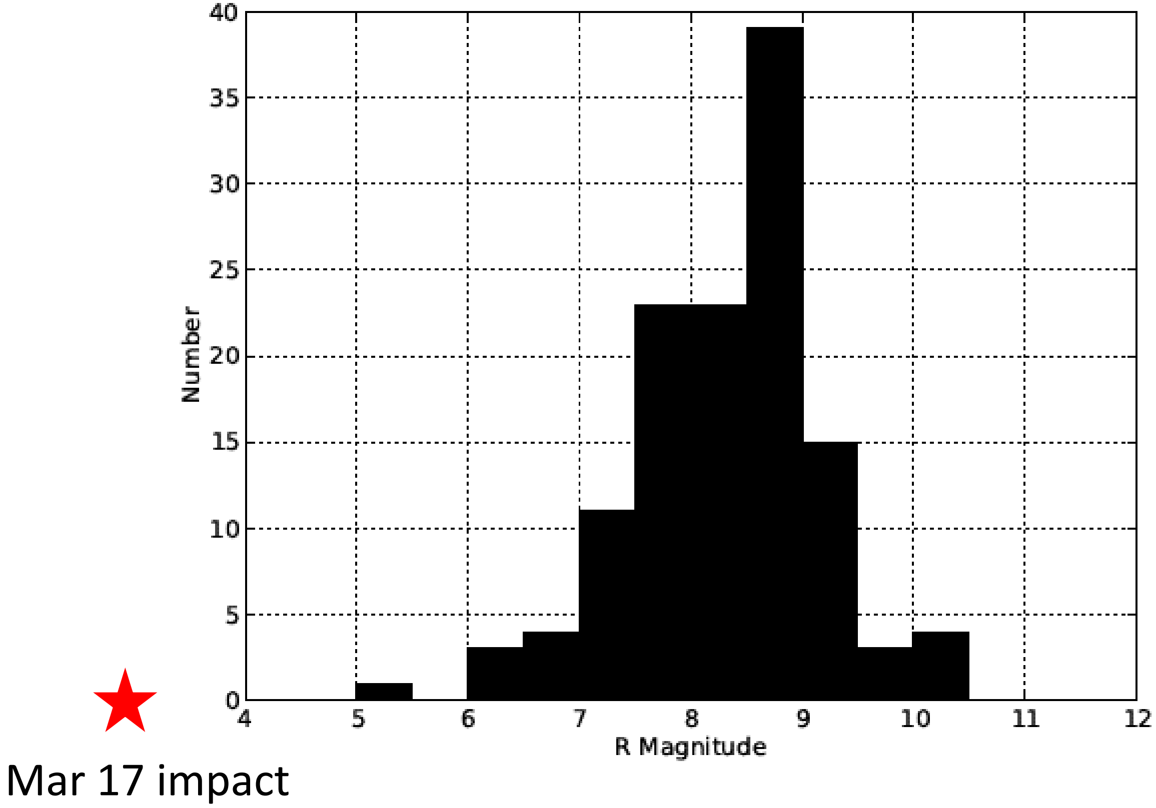
Impact Constraints

➡ Circular crater, impact angle constrained >15°

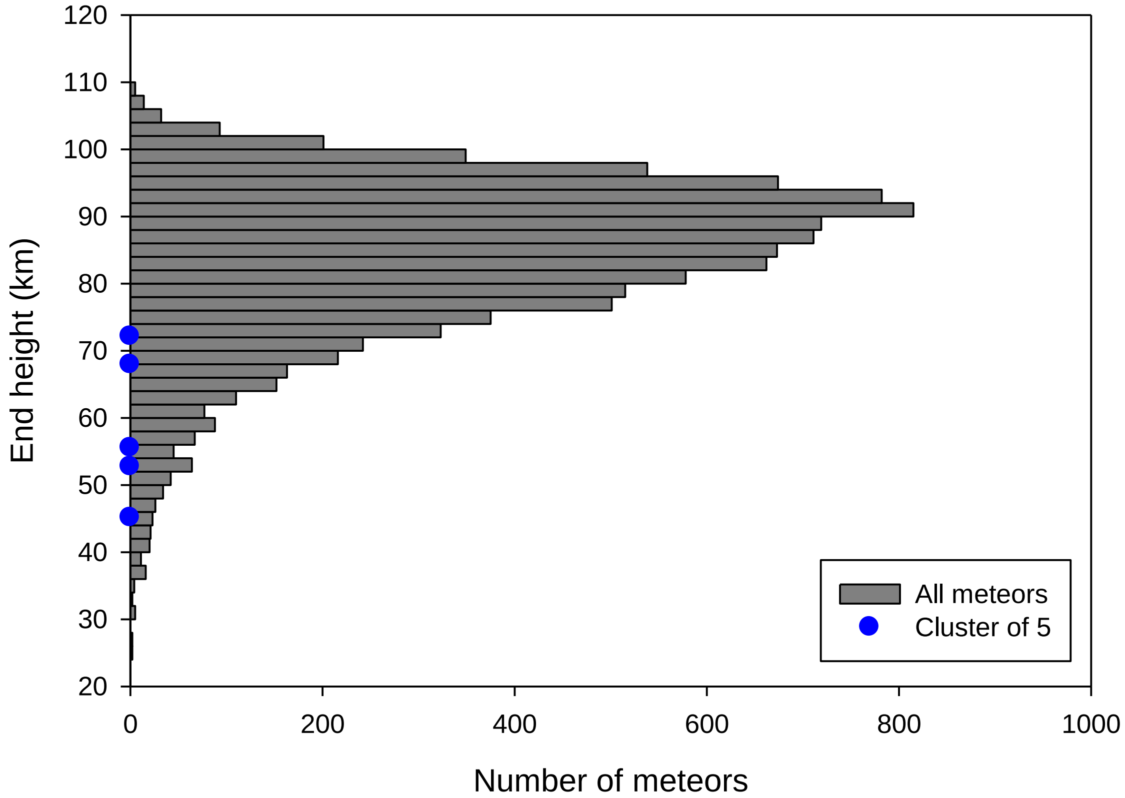
➡ HRZ – impact possible from SE or NW
LRZ – impact possible from SW
∴ no azimuth constraint (Robinson, personal comm. 2014a)

An impact from the SW is consistent with an impactor from the Virginid Meteor Complex.

Peak Impact Flash Magnitudes



All sky heights & masses



Cluster of 5 penetrated fairly deeply into the atmosphere.
Moderately large, 0.003 kg to 0.1 kg masses

Crater associated with Spanish flash on 11 Sep 2013

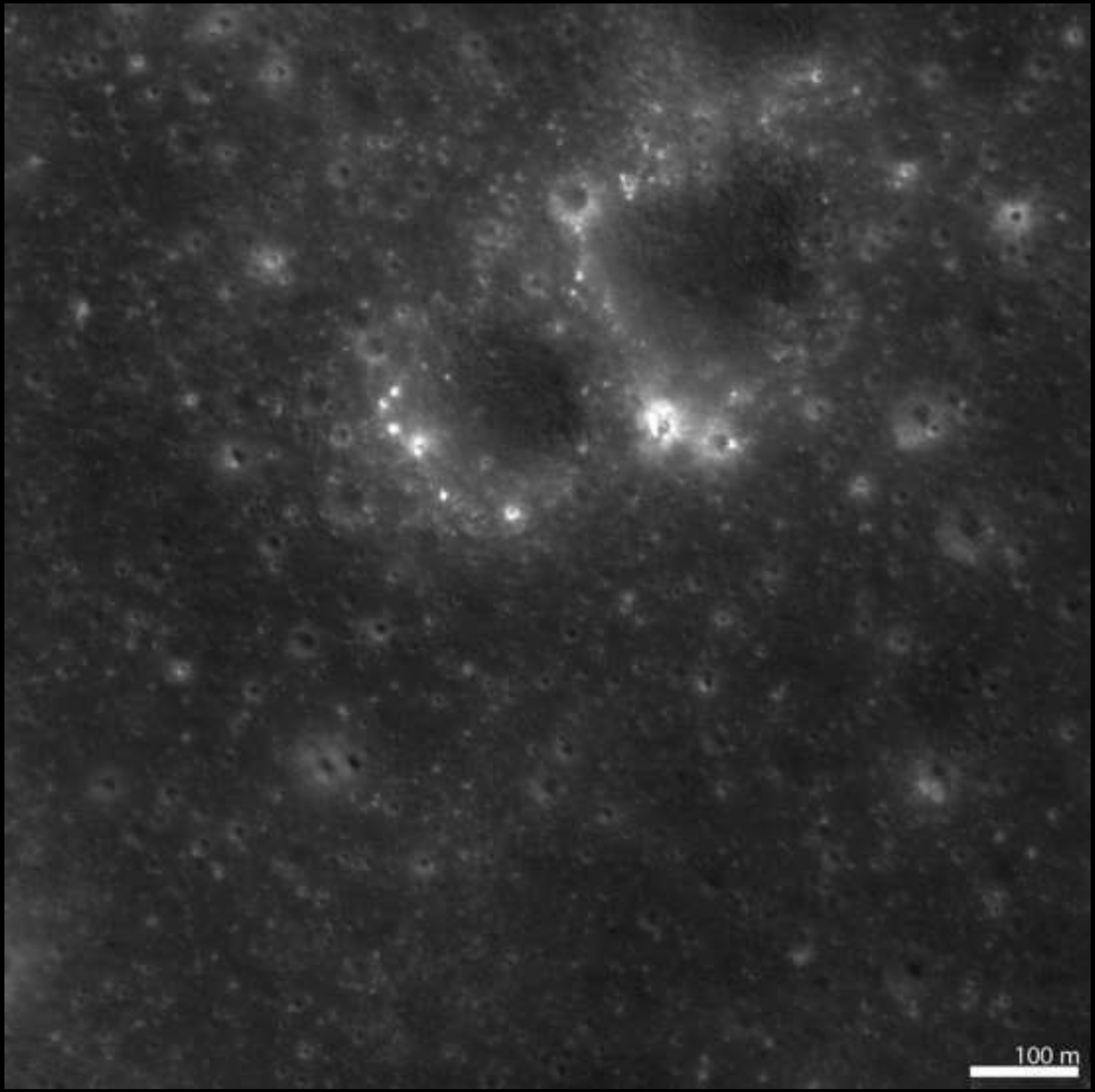


Image from Robinson (2014b)

NASA/GSFC/Arizona State University

<u>Crater info</u>

- Rim-to-rim diameter = 34 m
- Ejecta effects extend more than 500 m from the crater in all directions

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